mated the Coulomb energy to be 0.99 MeV and we should subtract this correlation from our value for the binding energy.

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HIGH-RESOLUTION STUDY OF LOW-ENERGY HEAVY COSMIC RAYS WITH LEXAN TRACK DETECTORS

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The response (track-etching rate) of Lexan polycarbonate detectors increases exponentially with the ionization rate of heavy nuclei ($Z \geq 10$). These detectors have been used to measure the charge composition and flux in 1967 of low-energy (200- to 400-MeV/nucleon) cosmic rays from $12 \leq Z \leq 28$.

We have discovered that sheets of ordinary Lexan polycarbonate[1] have a remarkable property that enables one to identify heavily ionizing particles with uniquely high resolution. This high resolving power may be explained by the assumption that the chemical reactivity along particle tracks in Lexan increases exponentially with ionization rate, in contrast to the linear response of conventional detectors such as nuclear emulsions and semiconductor crystals. Using Lexan detectors, we have identified 218 low-energy cosmic rays with $Z \geq 10$, of which 147 fall in the category of *VH* nuclei ($Z \geq 20$). The results show that the abundances of Mn and Cr are higher at low energy than at high energy[2] and thus provide new astrophysical information. Our results represent half the world data on *VH* nuclei with good charge resolution and the only data on the charge composition of low-energy nuclei with $Z \gtrsim 14$.[3] They are particularly valuable because the detecting plastics were flown at a much higher altitude (2 g/cm^2) than were previous detectors (4 to 10 g/cm^2),[2] so that the background introduced by fragmentation in air was small.

Figure 1 describes our method of particle identification in plastic sheets. In a recent paper[4] we showed that over small areas cellulose nitrate is sufficiently uniform in response that light isotopes such as B^{10} and B^{11} can be resolved. In a note added in proof we pointed out that Lexan polycarbonate, which records etchable tracks of nuclei with $Z \gtrsim 10$, has an even higher resolution

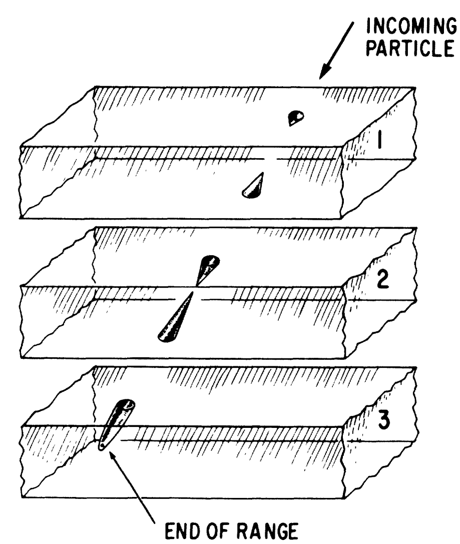

FIG. 1. NaOH etching solution attacks Lexan polycarbonate more rapidly along the trajectory of a heavily ionizing particle than elsewhere. The lengths of the hollow, etched cones increase with ionization rate. The last cone (sheet 3) has a rounded tip where the nucleus came to rest.

of heavy ions than cellulose nitrate. We have since found that its chemical composition and etching rate are highly uniform over many square meters, so that its response (rate of track etching) depends only on ionization rate, not on location of the track within the detector.

To study low-energy heavy cosmic rays, on 12 July 1967 we exposed a 0.4-m^2 stack of 40 sheets of Lexan polycarbonate, each 250 μ thick, at a depth of 2 g/cm^2 over Ft. Churchill, Manitoba, for 13 h in a horizontal orientation. The flight was arranged through the courtesy of Professor J. A. Earl.

In November, 1967, we etched part of the upper half of the stack in ultrasonically agitated, mechanically stirred 6.25 normal NaOH solution (containing 0.4% Benax surfactant) for 8 h at 70 ± 0.015°C. In March, 1968, we etched part of the lower half of the stack in the same way. Because of slow variations in the track-etching characteristics with time, data from the sheets processed in November and in March have been analyzed separately. In future flights we believe that this problem can be eliminated by processing all of the stack at the same time.

In our exposure the number of nuclei that came to rest in a given sheet and produced detectable tracks was about 0.03/cm^2. These tracks (see Fig. 1) were located by scanning at ~50×. The lengths of the end tracks (e.g., sheet 3 in Fig. 1) and of the corresponding cone tracks (sheets 1 and 2 in Fig. 1), together with the appropriate residual ranges, were measured at 2500× using a long-working-distance oil-immersion objective. All tracks at dip angles between 30° and 70° were accepted. Measurements made by different observers on the same set of cone tracks were reproducible to within ~1 μ.

In Fig. 2 are plotted cone-track lengths versus residual range for a representative sample of size 32 drawn from the 218 nuclei. A total of 973 cone tracks were measured. The number of cone tracks per event depends on the path length over which the primary ionization rate of the particle, J, exceeds the critical rate, J_C.[5] It increases from 1 for light ions such as Ne (events 17 and 36 in Fig. 2) to 10 or more for the heaviest ions (event 1).

We consider here only the nuclei with $Z \geq 12$, which produce at least two etchable cone tracks. A family of curves of cone length versus residual range can be drawn through the data for these nuclei. Certain curves are much more heavily populated than others. The problem is to identify

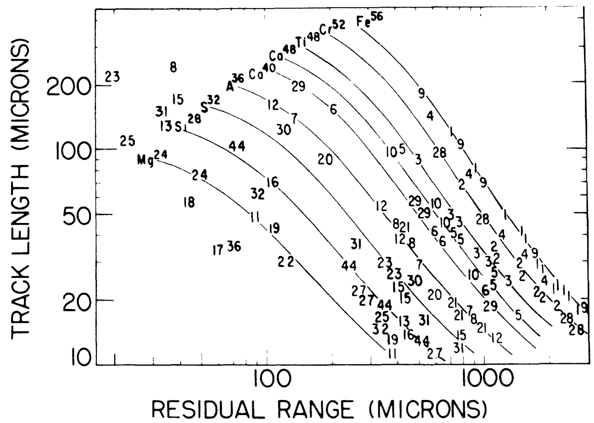

FIG. 2. Measurements of cone lengths versus residual range for 32 (a representative sample) of the nuclei that came to rest in the sheets etched in November, 1967. The curves were calculated from Eq. (2). Numerals are used both as data points and to identify events.

all the curves, even though at present ions heavier than Ne with suitable energy are not available in accelerators. By making two assumptions, we have been able to calculate a family of curves that fit the data and have obtained the distribution of cosmic-ray abundances shown in Fig. 3. Further, the curve calculated for Ne^{20} comes very close to data we have obtained for Ne^{20} ions from the Yale Hilac accelerator.

Our two assumptions are that (1) the most abundant nuclide with $Z > 14$ is Fe^{56}, and (2) the rate of lengthening of a cone track is given by

$$dR/dt = V_0 \exp[b(J - J_C)/kT] \text{ for } J \geq J_C, \qquad (1)$$

where T is the etching temperature, v_0 is the bulk etching rate of the plastic (1.06 μ/h at 70°C), R is the residual range measured from the low-energy end of the cone,[4] J is the primary ionization rate, and b and J_C are parameters chosen to give the best fit to the data. The exponential dependence of etching rate on J is understandable if the effect of a heavily ionizing particle is to lower the activation energy for the etching reaction.

To integrate Eq. (1) we approximate J (to better than 0.5 %) by a power function of residual range, $J(Z,A) = C(Z,A)R^{-\gamma(Z)}$. The parameters C and γ are determined for each nuclide by using the range-energy tables of Henke and Benton[6] and Bethe's primary ionization equation (justified for tracks in plastics in Ref. 5).

Curves of cone length versus residual range

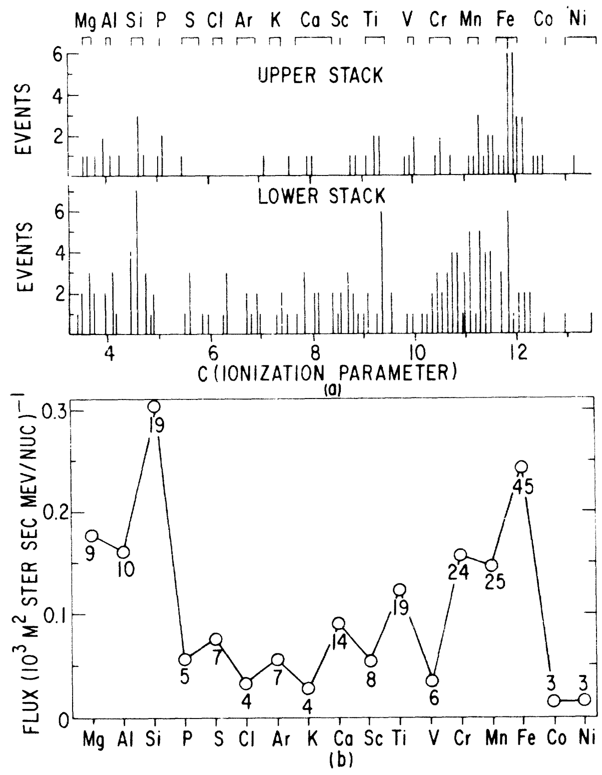

FIG. 3. (a) Composition of heavy cosmic rays uncorrected for recording efficiency. Path lengths to the top of the atmosphere ranged from 2.8 to 6.5 g/cm^2 in the upper stack and from 3.8 to 8.4 g/cm^2 in the lower stack. (b) Fluxes of heavy cosmic rays at the top of the atmosphere on 12 July 1967, calculated from (a) by averaging the contributions in the upper and lower stacks. The number of nuclei of each atomic number is indicated. The energy interval studied increases from 150 to 270 MeV/nucleon for Mg to 240 to 440 MeV/nucleon for Ni.

are computed by repeated numerical integration of Eq. (1) for different values of R_0:

$$t = v_0^{-1} \int_{R_0}^{R_0+L} \exp[-(CR^{-\gamma} - J_c)b/kT]dR, \quad (2)$$

where R_0 = residual range at which etching begins and $R_0 + L$ = residual range at which a cone track reaches length L in time t (= 8h in our experiment).

From a catalog of 125 pairs of values of C and γ corresponding to the possible nuclides between Ne^{20} and Ni^{64}, our colleague W. M. Schwarz has developed a computer program to select for each event which of the 125 curves calculated from Eq. (2) gives the best least-squares fit to the data for that event. The results are presented in Fig. 3(a), with brackets indicating the span of stable isotopes for each element. Since γ is almost independent of Z (decreasing from 0.503 for Ne to 0.463 for Ni), C is a convenient parameter to label the 125 nuclides and is the abscissa in Fig. 3(a). The value of C increases with atomic number as $\sim Z^{1.53}$ and with mass number as $\sim A^{0.5}$. From this and Eq. (2), it is easy to show that resolution of adjacent charges increases with Z, but that resolution of adjacent mass numbers decreases with A. In the present study, for a given event the standard deviation of cone track lengths from the least-squares curve corresponds to an uncertainty in A that is sometimes as small as one mass unit but is often as high as four mass units. Expressed in terms of charge, the uncertainty in Z varies from about 0.15 to 0.6 charge units. The fit of the data to Eq. (2) is very good and provides satisfactory evidence of an exponential response.

The differential intensities of the elements with $Z \geq 12$ have been plotted in Fig. 3(b), taking into account detection efficiency (100 % for $Z \gtrsim 18$, ~50 % for $Z = 14$, and ~35 % for $Z = 12$), energy interval covered, and absorption in the material above the detector. Fragmentation has not been taken into account but is a small source of error at 2 g/cm^2 of residual atmosphere. Events in Fig. 3(a) that fall between elements have been assigned to the nearest stable isotope. Except for these borderline cases and for the lightest ions studied (Mg and Al), charges appear to be satisfactorily resolved. The larger abundances of even-Z than odd-Z nuclei are physically reasonable but should not be regarded as established until direct calibration can be done in an accelerator and until the cause of the slow time variation in etching rates has been elucidated.

Our calculated flux of ***VH*** nuclei in an energy interval 200-400 MeV/nucleon is about 0.6 that measured by Freier and Waddington[7] at solar minimum; our flux of nuclei with $12 \leq Z \leq 19$ in the interval 160 to 350 MeV/nucleon is about 0.35 that measured at solar minimum.[7] The ratio of each flux in July, 1967 to the corresponding flux at solar minimum is consistent with a solar modulation function $\exp(-\Delta\eta/R\beta)$,[8] evaluated at the proper magnetic rigidity R and velocity βc, with $\Delta\eta \approx 0.9$.

It is important to establish whether the high Mn and Cr abundances result from spallation of Fe nuclei in interstellar matter or reflect the composition of cosmic-ray sources. From presently available data and calculations of appropriate cross sections, we believe at this point that the sources must contain significant amounts of Mn and Cr, unless the low-energy *VH* nuclei have passed through appreciably more than 5 g/cm^2 of interstellar matter. In a continuing study of the *VH* nuclei we are preparing to analyze a new Lexan stack that was recently exposed under only 1.8 g/cm^2 of air.

Potential future applications of this exponentially responding plastic detector include (1) studies of electron capture and loss and of high-energy heavy-ion reactions, (2) isotope resolution of heavy cosmic rays, (3) the composition of heavy nuclei in solar flares, (4) the composition of heavy cosmic rays with energies as low as 10 MeV/nucleon, and (5) the composition and energy spectrum of extremely heavy nuclei extending into the trans-uranium region.

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